Final Report

Final Project Report
CALFED Science Program Project Number: 1051
Original Project Term: July 1, 2007 – June 30, 2010
Revised Project Term: July 1, 2007 – Dec.19, 2008; June 2009 – Dec.31, 2011
Project Title: A Calibration-Free Approach to Modeling Delta Flows and Transport

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Project Summary:

Our project focuses on using real-time physical data from the Delta to develop models of flows and transport in sub-regions of the Delta that are not based on calibration to historical data sets. While there are a number of fixed moorings that provide velocity information in real-time (or nearly so) in the Delta, these are at particular locations, and may or may not coincide with regions of interest for future modeling analysis. To supplement these fixed measurements, and to provide a more robust predictive system, we will be developing Lagrangian drifters with real-time communication capabilities so that data from these rapidly deployable sensors can be incorporated into the analysis of Delta flows and transport.

In concert with these observational platforms, we are pursuing the development of fast, robust methods for estimating boundary conditions for regional hydrodynamic models in the Delta. The goal here is not to simulate the entire Delta, but rather to estimate flows and transport in smaller subregions of the Delta that may be of interest for particular operational decisions. The first site that we considered was the Sacramento River junctions with Georgiana Slough and the Delta Cross Channel, we are now beginning preparation for an experiment in the South Delta (Old and Middle Rivers).

The primary objective of this work is to develop and evaluate the performance of rapid data-based assessment of Delta flows and transport using inverse modeling approaches, including the collection and integration of real-time data from Lagrangian drifters.

<u>Budget Summary: Submitted Separately from Extramural Funds Accounting</u>

<u>List of Tasks and Activities Performed</u>

Our project was initially to focus nearly equally on the development of a drifter fleet and real-time modeling approaches. During the gap in funding due to the state budget crisis, however, we were able to continue work on the model development, so that once funding was reinstated we focused the majority of that effort on the drifter fleet. In the next sections, the scientific work is summarized, but I note here that a number of papers have emerged from both the observational and modeling work pursued under this grant.

<u>Task 1: Inverse Model Development</u>

We started with high-resolution forward model analysis of the region of the Sacramento River adjacent to Georgiana Slough (where the drifter experiments were performed, Figure 1) to establish the basic structure and variability of the flows. In order to produce Lagrangian trajectories quickly, we chose to use the MIKE family of hydrodynamic models. These simulations

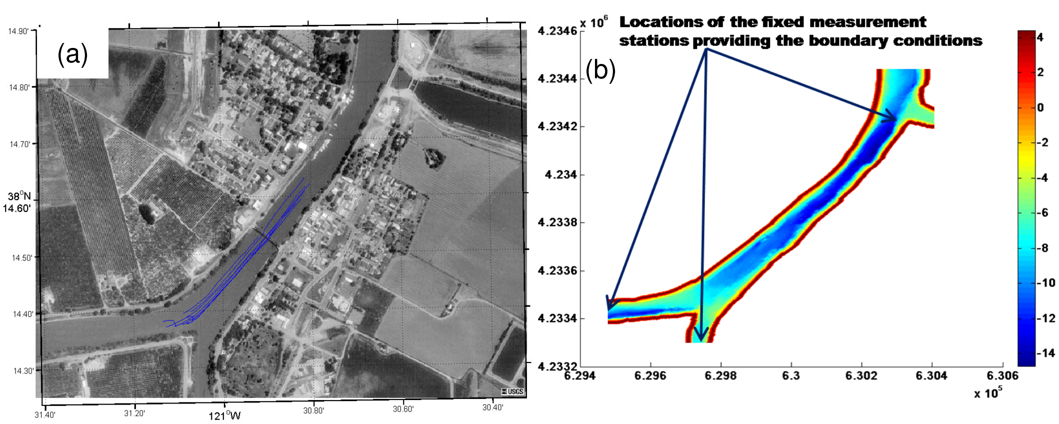

Figure 1: Reach of Sacramento River between Georgiana Slough and the Delta Cross-Channel. (a) Aerial photograph with real drifter trajectories overlaid in blue; (b) Detailed bathymetry and domain for numerical simulations.

will be used to provide more complete data sets for evaluating the performance of the inverse model calculation.

Three inverse methods were initially developed for use with Lagrangian drifter data. The adjoint approach, which requires iterations of a complete forward-backwards integration of the momentum equation, was compared with a linearized approach for which the data was assimilated using quadratic programming and a simple nudging approach in which an additional body force was applied in the model equations that accounted for model-data mismatch.

Preliminary comparisons of adjoint and simplified, linearized approach to the inverse model analysis suggested that the more complex adjoint approach was significantly slower than simplified approaches, and only slightly more accurate for estimating the initial conditions of the flow field (Figure 2).

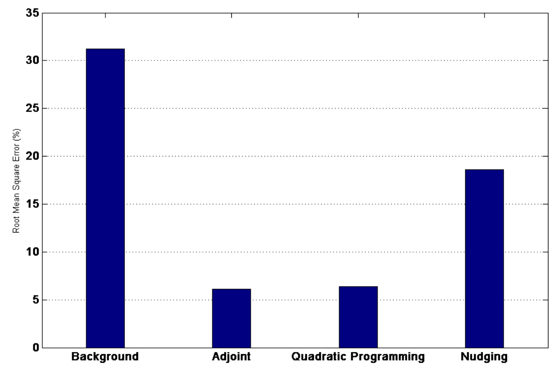

Figure 2: Comparison of relative root mean square errors in estimated initial conditions for three inverse approaches. "Background" represents the error in the starting values of the initial conditions.

As a result, we are now focusing on the use of a linearized approach for inverse model analysis for the Sacramento River site. Our decision here was based on a compromise between speed and accuracy; we have opted for very rapid state estimation, even though it may lead to slightly less accurate results.

We have now transitioned from estimating initial conditions to estimating open boundary conditions using Lagrangian measurements from the interior of the domain. We have formulated the open boundary conditions as a sum of tidal harmonics, thus reducing the parameter space for estimation to the amplitude and phase of the selected harmonics. Using harmonics also allows us to project boundary conditions forwards in time.

Our evaluation of the method involves looking at the mean square error at the boundaries using an identical twin approach. A MIKE hydrodynamic model creates both boundary conditions and Lagrangian trajectories in the region shown in Figure 1. The Lagrangian trajectories are assimilated using quadratic programming into a linearized model and flow boundary conditions are estimated; these estimates are then compared with flow at the boundary values produced by the MIKE simulation.

During the period of time that observations are available, the inverse model is able to effectively estimate the harmonic constants and reproduce the flows (Figure 3). The case in Figure 3 is actually the most difficult test of those considered, as it includes periods of flow reversal that occur in this reach of the Sacramento River in the fall season. Separate analysis of spring conditions (not shown) demonstrate that when the flows do not reverse direction, the

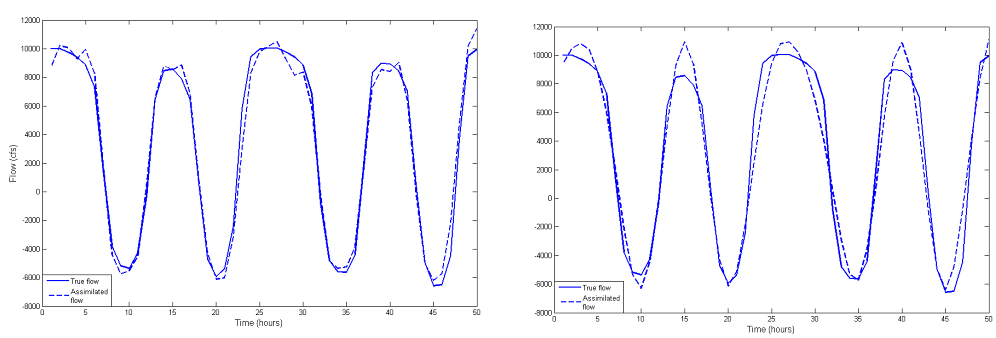

Figure 3: Comparison of MIKE flows ("True Flows" for identical twin experiment) and estimated flows using Lagrangian drifters from interior of the domain. (a) Inclusion of 6 tidal harmonics (M2, K1, MK3, M4, M6 and M8); (b) Inclusion of only 3 tidal harmonics (M2, K1 and MK3).

inverse model is even more effective at estimating the harmonic constants for the observation period.

At this site in the Sacramento River, it appears that 6 tidal harmonics (M2, K1, MK3, M4, M6, M8) are sufficient to accurately reproduce boundary flows (compare Figure 3a and 3b). For the 3 harmonic case, the relative error is approximately 40%; the error is reduced to approximately 10% when 6 harmonics are included.

Considering projections in time beyond the observation period, the ability of the harmonics to track the "true" values is somewhat limited. In Figure 4, the evolution of the root mean square error shows that within 3-5 days, the relative error has increased by a factor of 2-3. Even including an explicit spring-neap component did not improve the performance of the prediction. This appears to be due to the fact that tidal harmonics are a poor predictor of flows in this reach of the Sacramento River, where unsteady river flows influence the evolution.

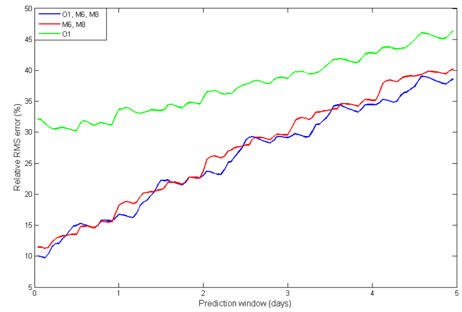

Figure 4: Evolution of the root mean square error for the period beyond the observation period. The starting value here reflects the root mean square error for the observation period. All three traces include M2, K1, MK3 and M4 tidal components; the legend notes which additional constituents are included for each case.

We now provide a brief summary of other modeling results that have been reported in the literature:

1. Quadratic programming. In this effort, under Calfed funding, we successfully developed an algorithm based on quadratic programming methods that pursued inverse modeling of one- and two-dimensional shallow water flows. This effort has been successfully applied to a network of channels and has been used to evaluate the ability to predict regional flows using real-time Lagrangian data [1,2].
2. Ensemble Kalman Filtering. In this effort, a parameter estimation method was applied to one- and two-dimensional shallow water flows [2].
3. Variational data assimilation. In a departure from our original plan, this modeling approach was applied in the spectral domain, rather than in time, which reduced the dimensionality of the problem. This approach has been successfully applied to networks of one-dimensional shallow water equations [3,4,5].
4. Extended Kalman Filtering. Recently, in conjunction with a related NSF project, we have also been pursuing an extension of the Kalman Filtering approach for one-dimensional shallow water flows [6].

Together, we now have a suite of inverse modeling approaches that are readily available for application to the Delta. One other pending effort would be based on the REALM model (development at Lawrence Berkeley National Laboratory), with which an Ensemble Kalman Filtering method may be appropriate. Absent that, however, we believe that the spectral domain variational data assimilation (item 3 above) provides us with a reliable, efficient method for estimating unknown boundary or initial conditions for flows in regions of the Delta.

<u>Task 2: Drifter Development</u>

Figure 5: Current fleet of active drifters

A set of ~10 GPS-logging drifters were developed and deployed. In 2008, the drifters did not have real-time data communication capabilities, but rather logged data internally. Using those drifters, we performed a series of preliminary deployments in the Sacramento River (Figure 1) at the junction of the river and Georgiana Slough. Although these drifters did not yet have real-time communication capabilities, the data from them was used in a retrospective analysis of the ability of our inverse modeling techniques to incorporate Lagrangian data in a region that includes a channel junction.

Software for visualization of drifter trajectories has been developed. It was also used in our retrospective analysis, but we are now using it in real-time now that the drifters are able to communicate in real-time.

In the latter half of the project, new capabilities were developed in the prototype drifters. Specifically, they now have wireless communication, active buoyancy control and horizontal thrusting capabilities which will allow them to follow a variety of drifting strategies (including changing their strategies during deployments using the wireless communication capabilities). Examples of drifting strategies may include: the drifters remain near the surface to simulate the trajectories of Delta smelt; the drifters migrate laterally (either tidally or diurnally) to evaluate hypotheses regarding how Delta smelt (and other species) migrate upstream; the drifters maintain their position along the lateral edges of channels to evaluate the transport of salmon smolt; the drifters repeatedly profile vertically in order to effectively sample the depth-averaged velocity. At the moment, we have a fleet of approximately 10 of these “active drifters” (Figure 5). They have been designed for easy servicing (Figure 6), which will allow for rapid battery changes and repairs or adjustments in the field. For a brief demonstration of their capabilities (in a shallow tank in the laboratory), we provide two videos. The first demonstrates the GPS control and thrusting and can be viewed at http://www.youtube.com/watch?v=ptrZlYx4Xmo; the second demonstrates the buoyancy control and some thrusting (http://www.youtube.com/watch?v=-vx2G414QEs). In the past 6 months, we have been working to expand our fleet, and are beginning the fabrication of the full-scale fleet of approximately 50 active drifters. We are on pace to have this fleet completely built out by Summer 2011 for our large-scale integrated experiment.

<u>Task 3: Integrated Experiment</u>

A number of integrated experiments have been performed at sites throughout the Bay and Delta, including specifically Old and Middle Rivers in the Sacramento-San Joaquin Delta and South San Francisco Bay. In each case, drifter trajectories were successfully recorded and the rapid deployment of drifters was demonstrated. In the Delta experiments (August-September 2010, March 2011), we began to explore the capabilities of the drifters to do shoreline avoidance. Most importantly, in a larger-scale experiment near Franks Tract in the Central Delta in summer of 2011, we demonstrated the real-time capabilities of the drifter-model system, which successfully tracked and projected flow paths during the experiment period.

Figure 6: Current prototype, including removable base for battery and electronics access

<u>Task 4: Analysis and Evaluation</u>

Throughout the project, we were continuously analyzing and evaluating the performance of the drifters and the modeling approaches. These evaluations led to modifications in our modeling approach and revisions in the design of the drifters, both physically and in their communications. The evaluation of the larger, integrated experiment from Summer of 2011 suggests that the model-drifter platform can successfully be used as a rapid-response means to measure and predict flow paths. An important aspect of this approach is that it does not rely on historical data to calibrate the hydrodynamic model, but instead makes use of the streaming data from the drifters to improve the prediction of flows and transport. As such, the system we have developed would be particularly useful in situations where the Delta is altered suddenly (i.e., large-scale levee failures) so that historical data may not be representative of current conditions. In this scenario, a rough, but rapid, estimate of flow and transport may be important in evaluating management of the Delta, including containment of spills or sediments, and the functioning of South Delta pumps.

References Cited (Complete list of publications appears below in Deliverables)

[1] Comparison of two data assimilation algorithms for shallow water flows, I. Strub, J. Percelay, O.-P. Tossavainen, A. Bayen, Networks and Heterogeneous Media, (4)2, pp. 409-430, June 2009, doi:10.3934/nhm.2009.4.409

[2] Inverse estimation of open boundary conditions in tidal channels, I. Strub, J. Percelay, M. Stacey and A. Bayen, Ocean Modelling, 29(1), pp. 85-93, March 2009, doi:10.1016/j.ocemod.2009.03.002

[3] Data reconciliation of an open channel flow network using modal decomposition, Q. Wu, X. Litrico, A. Bayen, Advances in Water Resources, 32(2), pp. 193–204, February 2009, doi:10.1016/j.advwatres.2008.10.009

[4] Inverse modeling for open boundary conditions in channel network. Q. Wu, M. Rafiee, A. Tinka and A. Bayen, In Proceedings of the 48th IEEE Conference on Decision and Control, Shanghai, China, Dec 2009.

[5] Quadratic programming based data assimilation with passive drifting sensors for shallow water flows. A. Tinka, I. Strub, Q. Wu and A. Bayen, In Proceedings of the 48th IEEE Conference on Decision and Control, Shanghai, China, Dec 2009.

[6] Kalman filter based estimation of flow states in open channels using Lagrangian sensing. M. Rafiee, Q. Wu and A. Bayen, In Proceedings of the 48th IEEE Conference on Decision and Control, Shanghai, China, Dec 2009.

Achieved Objectives, Findings and Contributions:
The key findings are outlined above, particularly under Tasks 1 and 2, and the contributions will be summarized below in "Deliverables"; here we focus on the broad objective of the project, which was to develop a method for predicting Delta flows that can be deployed rapidly and is not dependent on historical data for calibration. In this project, we have successfully completed both the development and testing of an integrated drifter-model system to do real-time quantification and projection of flows and transport in the Delta. Our drifter fleet, which consists of approximately 50 individual drifters, can be rapidly deployed in response to unforeseen events. Streaming data from those drifters with continuous communication is used to calibrate a simplified hydrodynamic model of the Delta, which can be used to project conditions over several days to a week or two.

Management Implications of Project Findings:
What makes this model-drifter platform distinct from previous approaches to simulating Delta flows is that it does not rely on historical data to calibrate the hydrodynamic model, but instead makes use of the streaming data from the drifters to improve the prediction of flows and transport.

As such, the system we have developed would be particularly useful in situations where the Delta is altered suddenly (i.e., large-scale levee failures) so that historical data may not be representative of current conditions. In this scenario, a rough, but rapid, estimate of flow and transport may be important in evaluating management of the Delta, including containment of spills or sediments, and the functioning of South Delta pumps.

Project Deliverables:
In addition to presentations at the Bay-Delta Science Conference in Fall 2010 and our technical reports (semi-annually and this final report), this project has resulted in XXX publications to date:

Rafiee, M., Wu, Q. and Bayen, A. (2009) "Kalman filter based estimation of flow states in open channels using Lagrangian sensing." In *Proceedings of the 48th IEEE Conference on Decision and Control*, Shanghai, China, Dec 2009.

Strub, I., Percelay, J., Tossavainen, O.-P., Bayen, A. (2009) "Comparison of two data assimilation algorithms for shallow water flows," *Networks and Heterogeneous Media*, (4)2, pp. 409-430, June 2009, doi:10.3934/nhm.2009.4.409

Strub, I., Percelay, J., Stacey, M.T. and Bayen, A. (2009) "Inverse estimation of open boundary conditions in tidal channels," *Ocean Modelling*, 29(1), pp. 85-93, March 2009, doi:10.1016/j.ocemod.2009.03.002

Tinka, A., Strub, I., Wu, Q. and Bayen, A. (2009) "Quadratic programming based data assimilation with passive drifting sensors for shallow water flows." In *Proceedings of the 48th IEEE Conference on Decision and Control*, Shanghai, China, Dec 2009.

Tossavainen, O., Percelay, J., Stacey, M.T., Kaipio, J.P. and Bayen, A. (2011), "State estimation and modeling error approach for 2-D shallow water equations and Lagrangian measurements," *Water Resour. Res.*, 47, W10510, doi:10.1029/2010WR009401.

Wu, Q., Litrico, X., and Bayen, A. (2009) "Data reconciliation of an open channel flow network using modal decomposition," *Advances in Water Resources*, 32(2), pp. 193–204, February 2009, doi:10.1016/j.advwatres.2008.10.009

Wu, Q., Rafiee, M., Tinka, A. and Bayen, A. (2009) "Inverse modeling for open boundary conditions in channel network." In *Proceedings of the 48th IEEE Conference on Decision and Control*, Shanghai, China, Dec 2009.